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on

NSR 22-009-288

A Study of Fluid Dynamics of Gaseous Nuclear Rockets

Work this quarter has been primarily concentrated on the empirical correlations of vortex data. The results of this study are contained in C. A. Rodoni's thesis (Ref. 1). The major results of his study are summarized in Appendix A. Rather than publish a report on this study at the present time, the information obtained from this study will be incorporated in the comprehensive review of the state of knowledge of vortex flows and how such flows relate to fluid dynamic containment which will constitute the final report on this contract. Copies of the thesis are available upon request.

W. S. Lewellen
Project Supervisor

October 1, 1969

Appendix A

Summary
of

An Investigation of the Flow Parameters of a Confined Turbulent Vortex

Carl Arthur Rodoni

In this study an attempt was made to find out to what extent empirically derived correction terms to laminar theories can be used successfully to predict turbulent results, and to look for direct correlations of the characteristic flow parameters in terms of the independent flow variables of the system.

A literature search was conducted to obtain the experimental data to be used in the correlations (see Ref. 2). A computer program was then written to find the optimum grouping of independent flow parameters which would fit the dependent parameters to a given curve.

Using this curve fitting method, empirical correlations were attempted for the ratio of the tangential velocity at the peripheral wall to the jet injection velocity (v_w/v_{jet}), the ratio of the tangential to radial velocities (v/u), the ratio of the circulation ($\Gamma = vr$) at the radius of the exhaust hole to the circulation just outside of the peripheral wall boundary layer ($\Gamma_e/\Gamma_{.8}$), the ratio of the circulation at the radius of the exhaust hole to the maximum achievable circulation (Γ_e/Γ_{ideal}), the ratio of the mass flow through the vortex to the "no-swirl" mass flow ($\bar{W}_o$), and the maximum tangential Mach number in the vortex (Mt_{max}).

One of the best correlations achieved in this work was for the normalized mass flow ratio ($\bar{W}_o$). The empirical correlation shown in Fig. 1 allows the prediction of the mass flow ratio $\bar{W}_o$ for a vortex in terms of

the parameters r_e/r_o, the ratio of the exhaust hole radius to the outer wall radius; A_i/A_e, the ratio of inlet area to the exhaust area; L/D, the length-to-diameter ratio of the chamber; and N_H, the number of exhausts. It was found that $\bar{W}_o$ was primarily a function of r_e/r_o and L/D for L/D>2 and primarily a function of r_e/r_o, only, when L/D<2.

The momentum balance theory of Kendall and Roschke (Ref. 3) is also substantiated by the recovery factor data. The results shown in Figs. 2 and 3 show that correlations for the recovery factor can be obtained in terms of the momentum balance theory, within the range of the expected data scatter. According to these correlations, v_w/v_{jet} is primarily a function of the ratio of the injection area to the peripheral wall area (A_i/A_w).

The effective skin friction coefficient for the peripheral wall has been shown to be larger than that predicted by the turbulent flat plate formula. (See Fig. 4). This increase in C_f is due to the presence of other dissipative factors in the flow such as turbulent shear terms, wall curvature, jet mixing, etc. The skin friction coefficient calculated over the chamber end-walls is also considerably higher than that predicted by turbulent flat plate results (Fig. 5).

The correlations shown in Figs. 6 and 7 show that the velocity ratio (v/u) is a function of the parameters r_e/r_o and L/D as well as the area ratio A_i/A_w predicted by the momentum balance theory. The presence of these geometrical terms not predicted by the momentum balance theory tends to indicate the presence of other flow phenomena which the theory has ignored.

One explanation for the presence of the r_e/r_o and L/D terms as well as the increased dissipation observed in the vortices is a flow phenomenon which may be called "exhaust hole choking." This effect may be caused by the fact that when the fraction of the energy invested in the swirl is above a certain value, further increases in the swirl actually reduce the angular momentum which can pass through the exhaust holes (See Ref. 4). The flow then must rearrange itself to increase the level of dissipation and thus reduce the swirl at the exhaust.

The fact that the correlations presented for the ideal circulation ratio in Figures 8, 9 and 10 have much less data scatter than the recovery factor correlations in Figures 2 and 3 or the circulation ratio correlations of Figures 11 and 12 argues that the flow regions near the peripheral wall and in the center of the vortex are coupled in some manner.

The flow mechanism of "exhaust hole choking" not only accounts for this flow coupling, but also provides explanations for the observed parametric trends in the empirical correlations. The postulation of this "exhaust hole choking" effect would account for the deviation of the velocity ratio correlations of Fig. 6 and 7 from the values of v/u predicted by the momentum balance theory as well as the L/D dependence of C_f in Fig. 5.

Although, the correlations for the ideal circulation ratio appear to establish a definite flow dependence, the trends shown should be viewed with a certain amount of reservation. According to these correlations (shown in Figs. 8 and 9), Γ_e/Γ_{ideal} is a function of r_e/r_o, A_i/A_w, and P_o/P_e. These correlations do have very little data scatter involved in them, but they also contain very few data points, and the pressure ratio

dependence shown in them may be valid over a limited range only. Therefore, the correlation shown in Fig. 10 is preferable to these, even though it has greater data scatter. This is because Fig. 10 contains more data points, and has a more reliable parameter dependence. According to this correlation Γ_e/Γ_{ideal} is a function of r_e/r_o, A_i/A_w, and Re_t.

The differences between the theoretical curves and data points on Fig. 11 can be used to define an "effective eddy viscosity". Relatively small differences in circulation lead to large values of eddy viscosity as seen in Fig. 12.

The three-dimensional theory on which Fig. 12 is based (Ref. 5) checks out well with experimentally observed flow patterns. In Fig. 13, the values of the flow stagnation radius ($\hat{r}/r_o$) as measured by Travers in Ref. 6 are shown to be in good agreement with the flow model predictions. Thus if the flow model breaks down, it must do so at some point inside the stagnation radius.

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3. Roschke, E. J., "Heat Transfer and Fluid Mechanics," California Institute of Technology, Jet Propulsion Laboratory, Space Programs Summary No. 37-20, Volume IV (1963).

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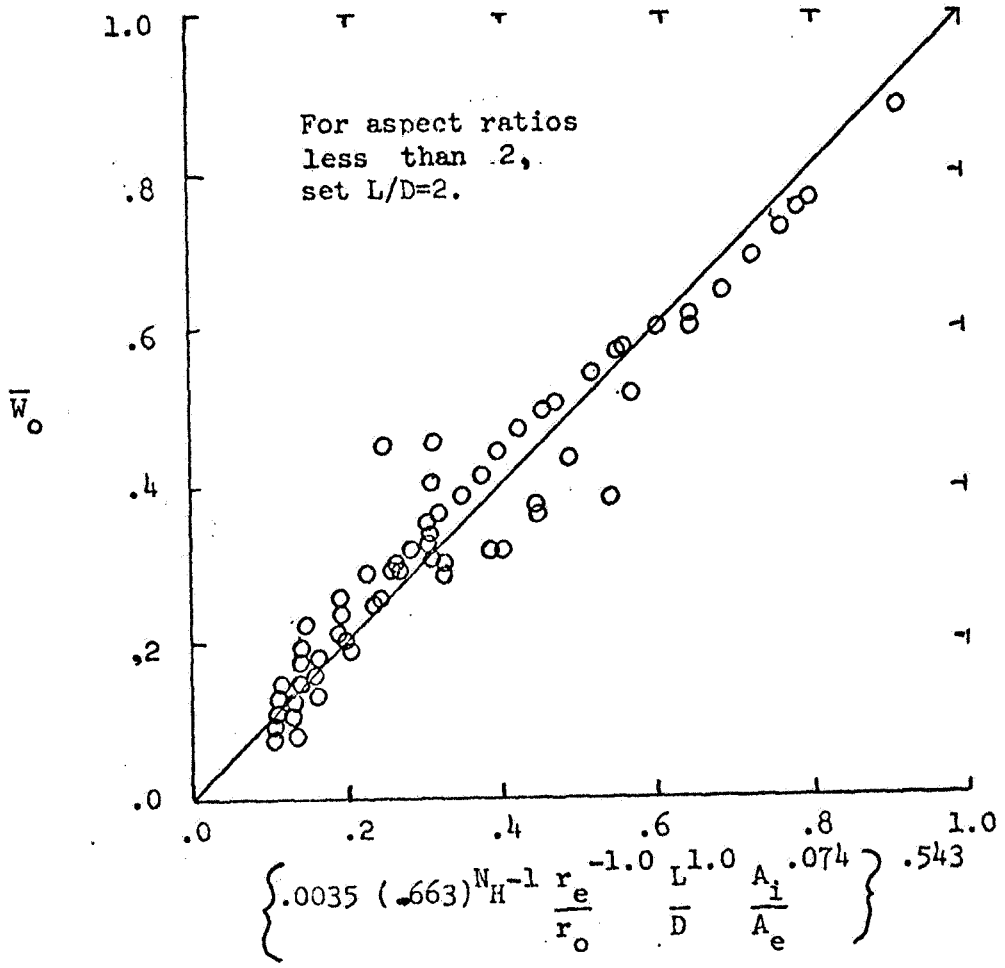

FIG. 1 The ratio of the mass flow through the vortex chamber to the "no-swirl" mass flow as a function of r_e/r_o, the ratio of the exhaust hole radius to the outer wall radius; A_i/A_e, the ratio of the inlet area to the exhaust area; L/D, the length-to-diameter ratio of the chamber and N_H, the number of exhausts.

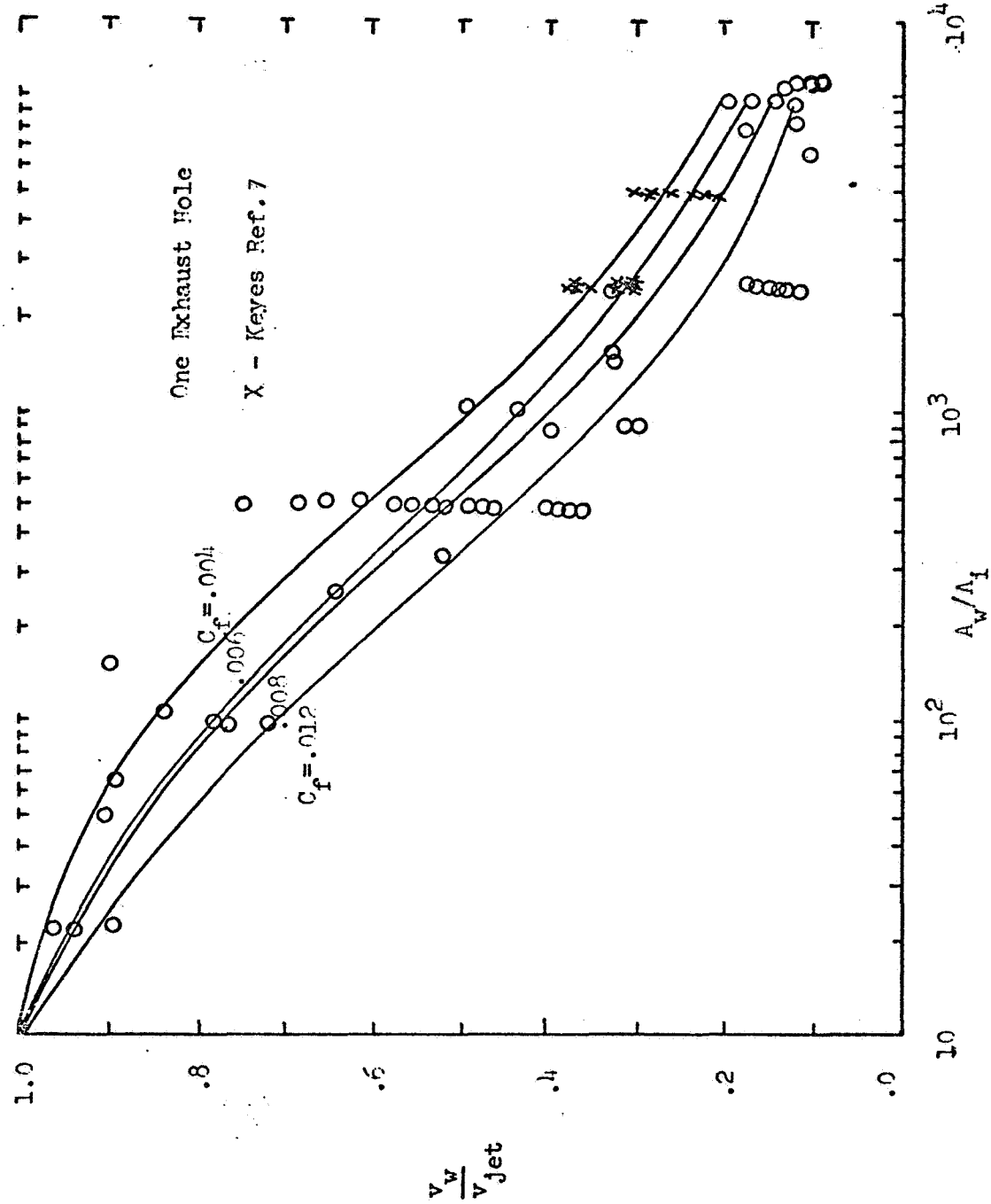

FIG. 2 The recovery factor V_w/V_{jet} as a function of A_w/A_1, the ratio of the peripheral wall area to the injection area, with the coefficient of friction C_f as a parameter.

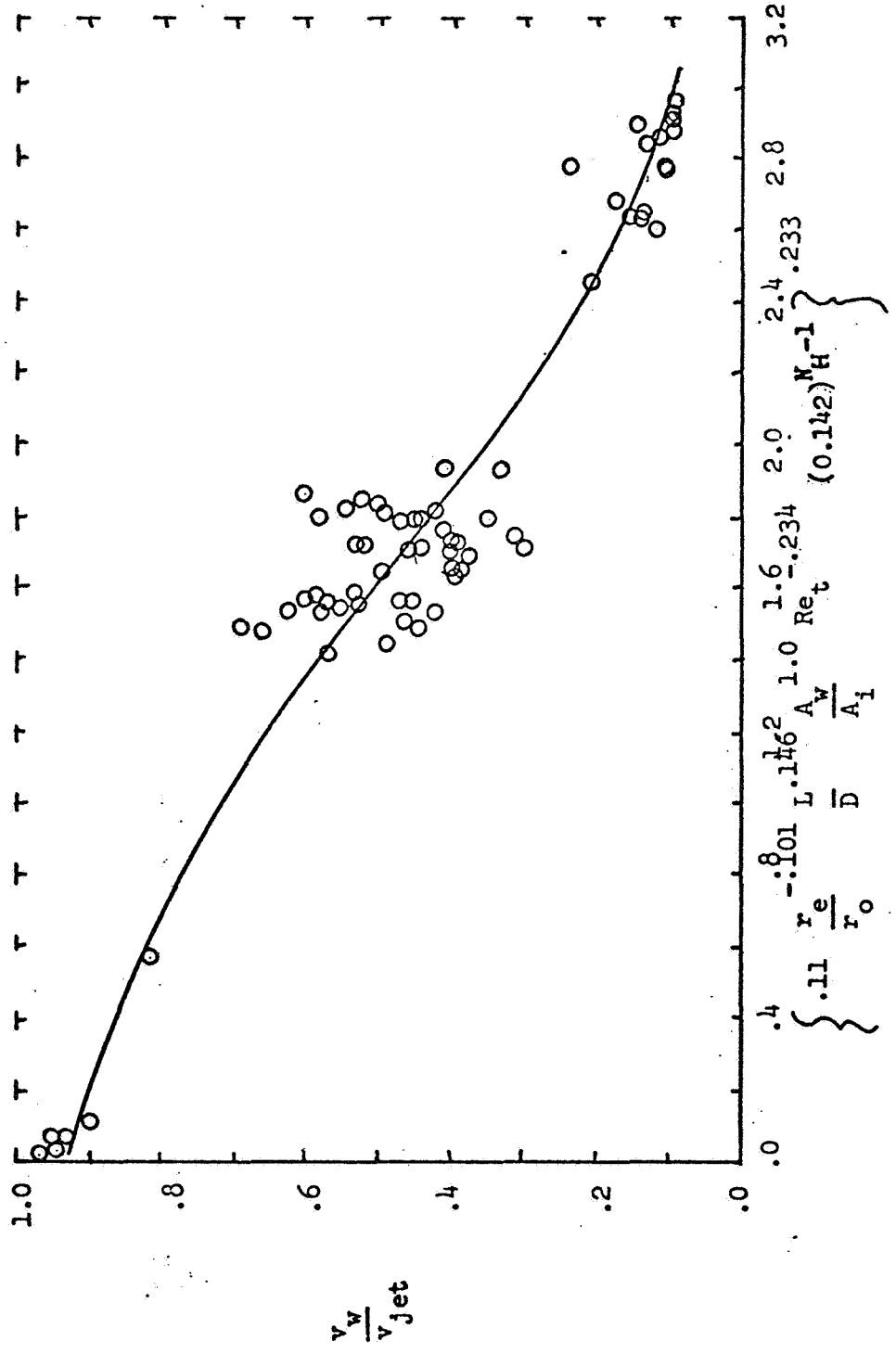

FIG. 3 The recovery factor V_w/V_{jet} as a function of r_e/r_o, the ratio of the exhaust hole radius to the outer wall radius; L/D, the length-to-diameter ratio of the chamber; A_w/A_i, the ratio of the peripheral wall area to the injection area; N_H, the number of exhaust holes; and Re_t, the tangential Reynolds number.

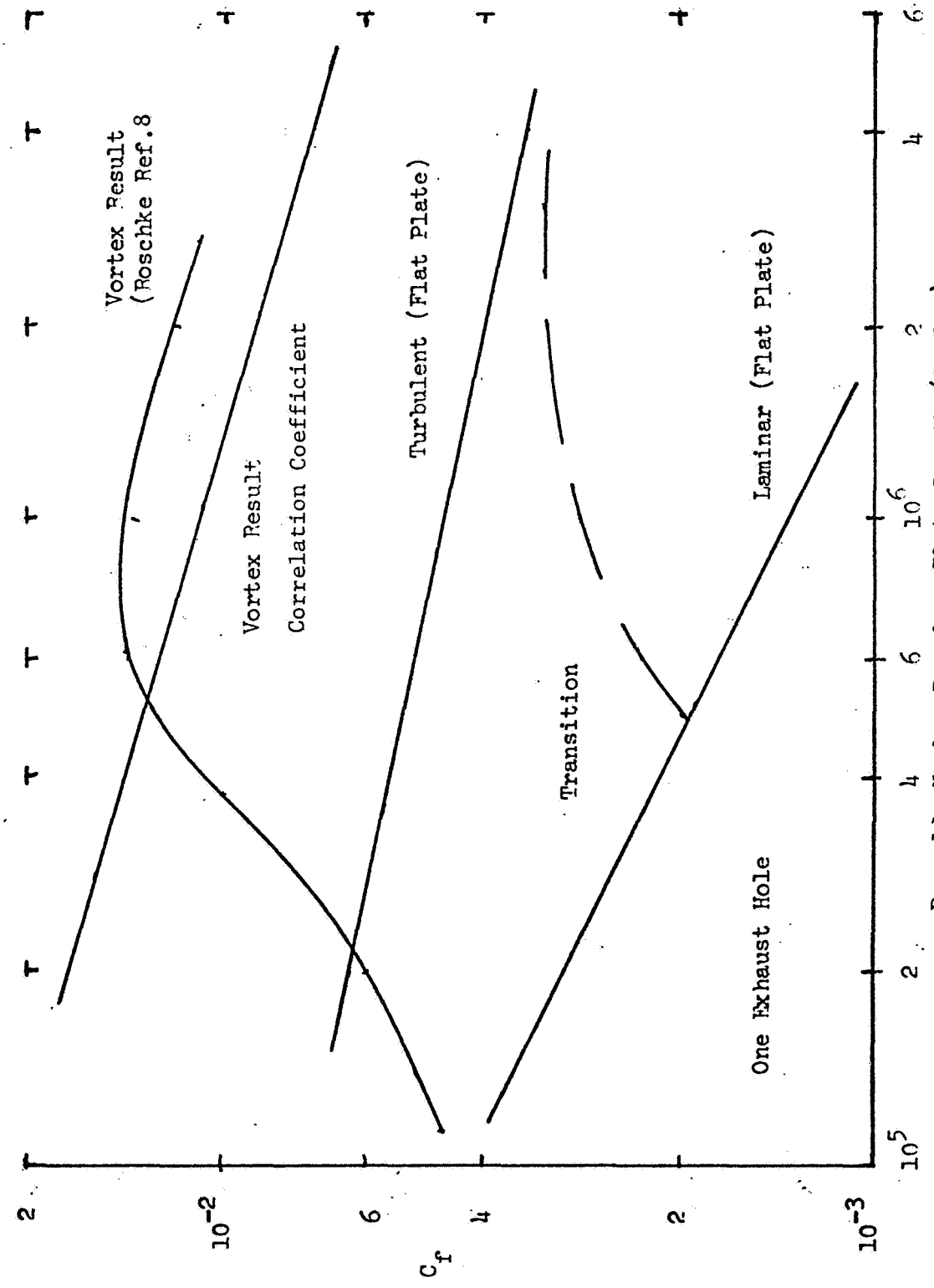

FIG. 4 Comparison of "effective" skin friction coefficient with flat plate results.

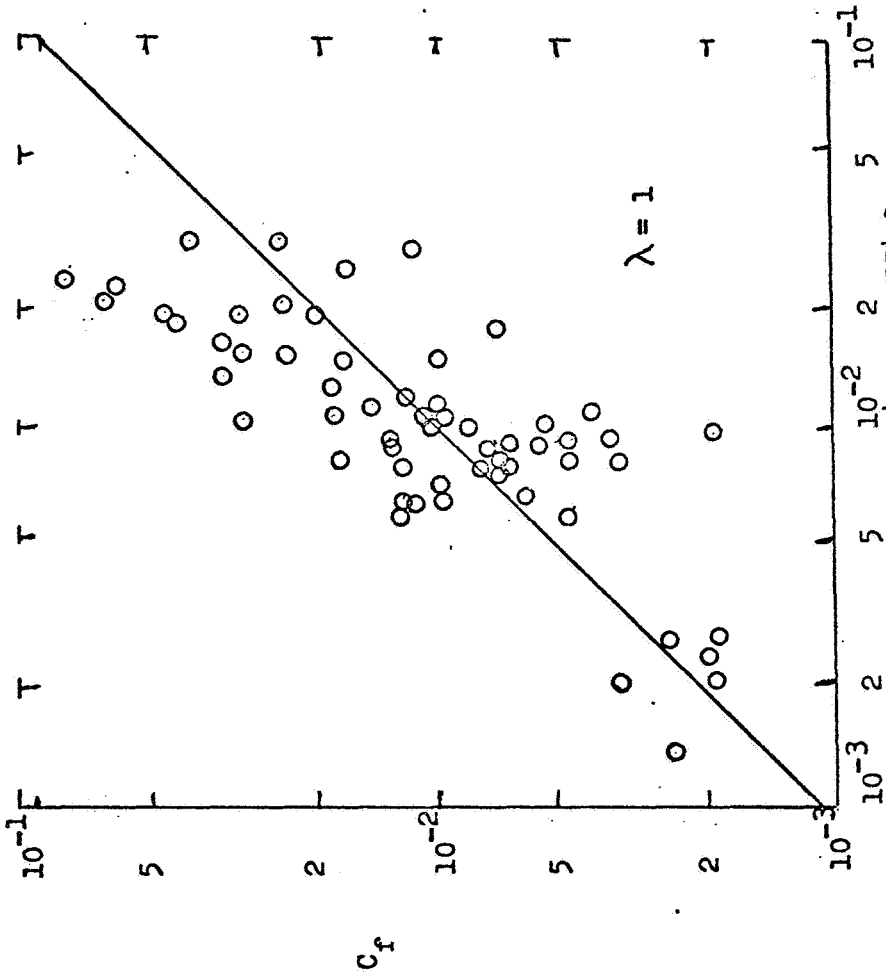

FIG. 5 The variation of the effective end-wall skin friction coefficient with L/D, ν/u, and Re_t.

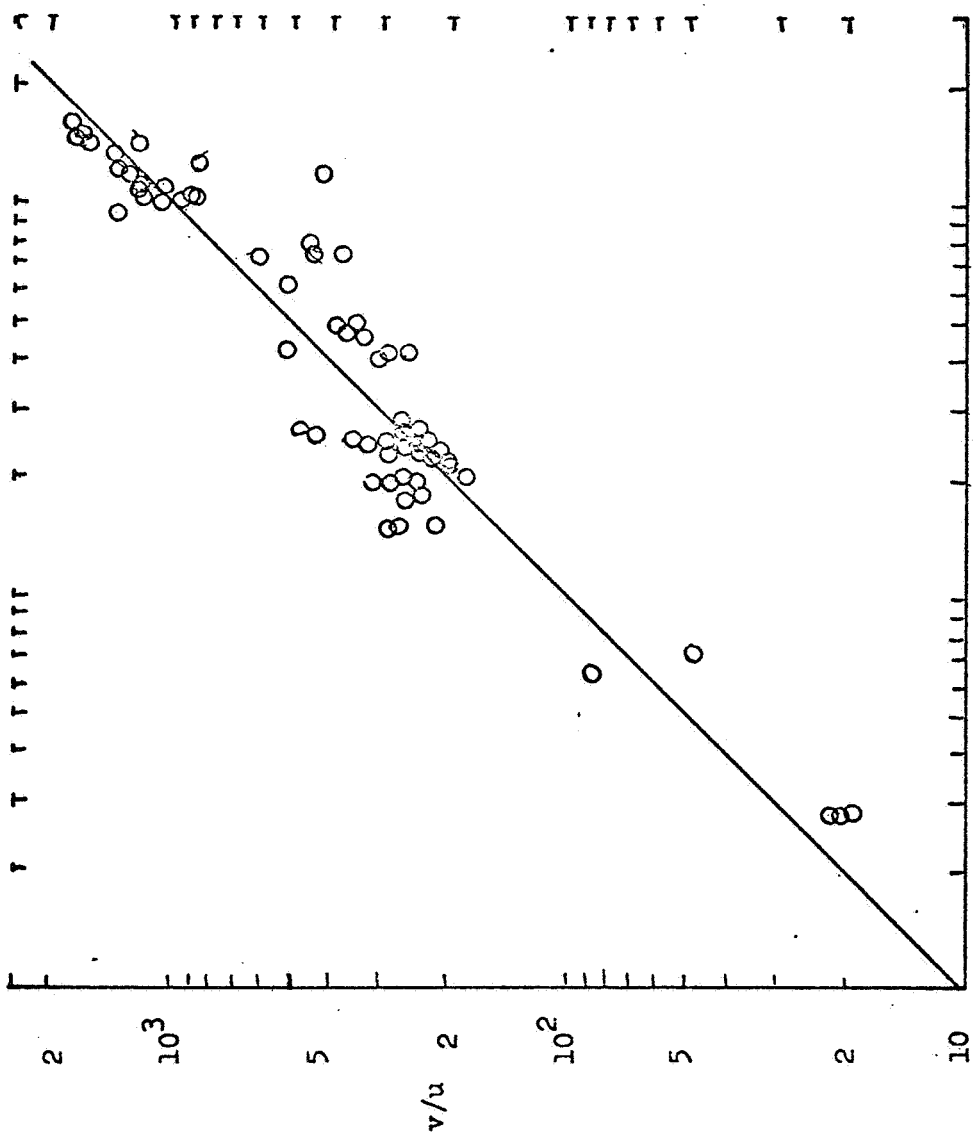

FIG. 6 The velocity ratio as a function of r_e/r_o, A_w/A_i, L/D, and N_H.

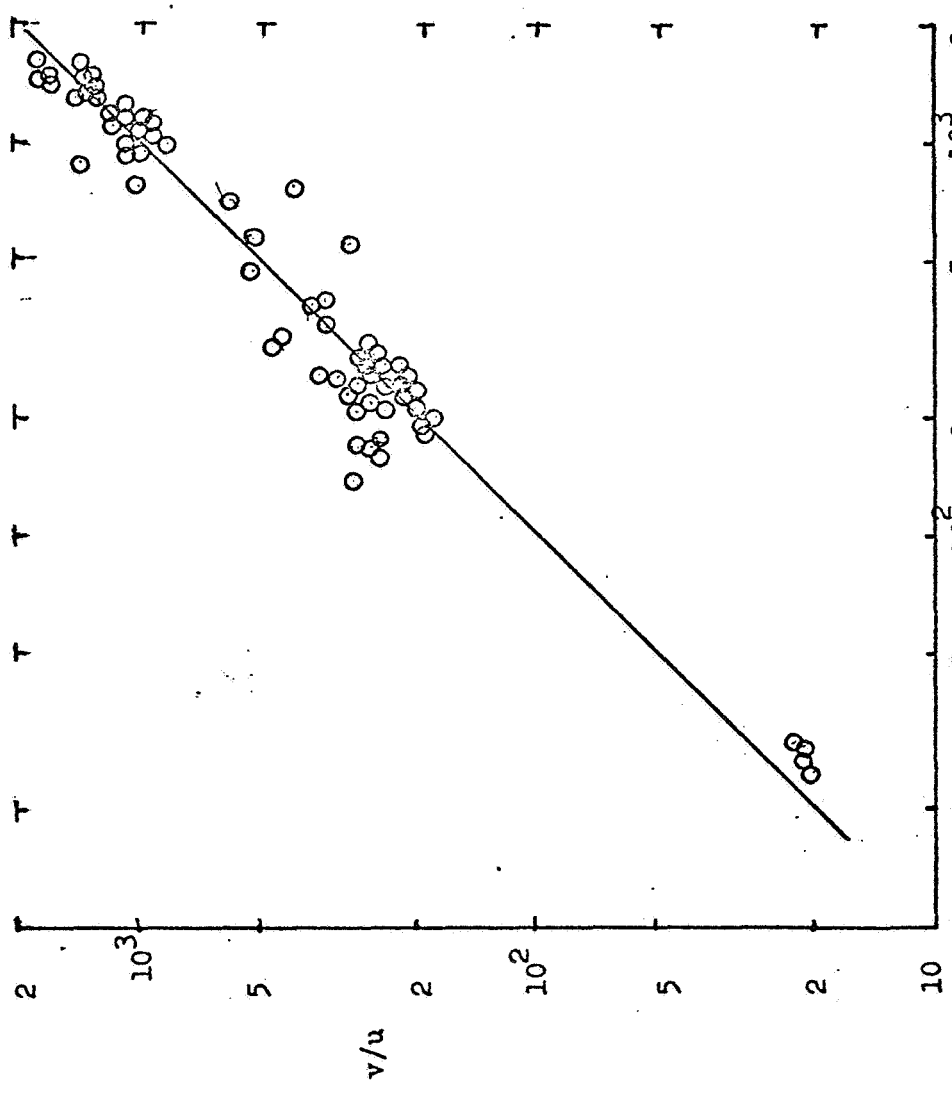

FIG. 7 The velocity ratio as a function of r_e/r_o, A_w/A_i, L/D, N_H, and Re_t.

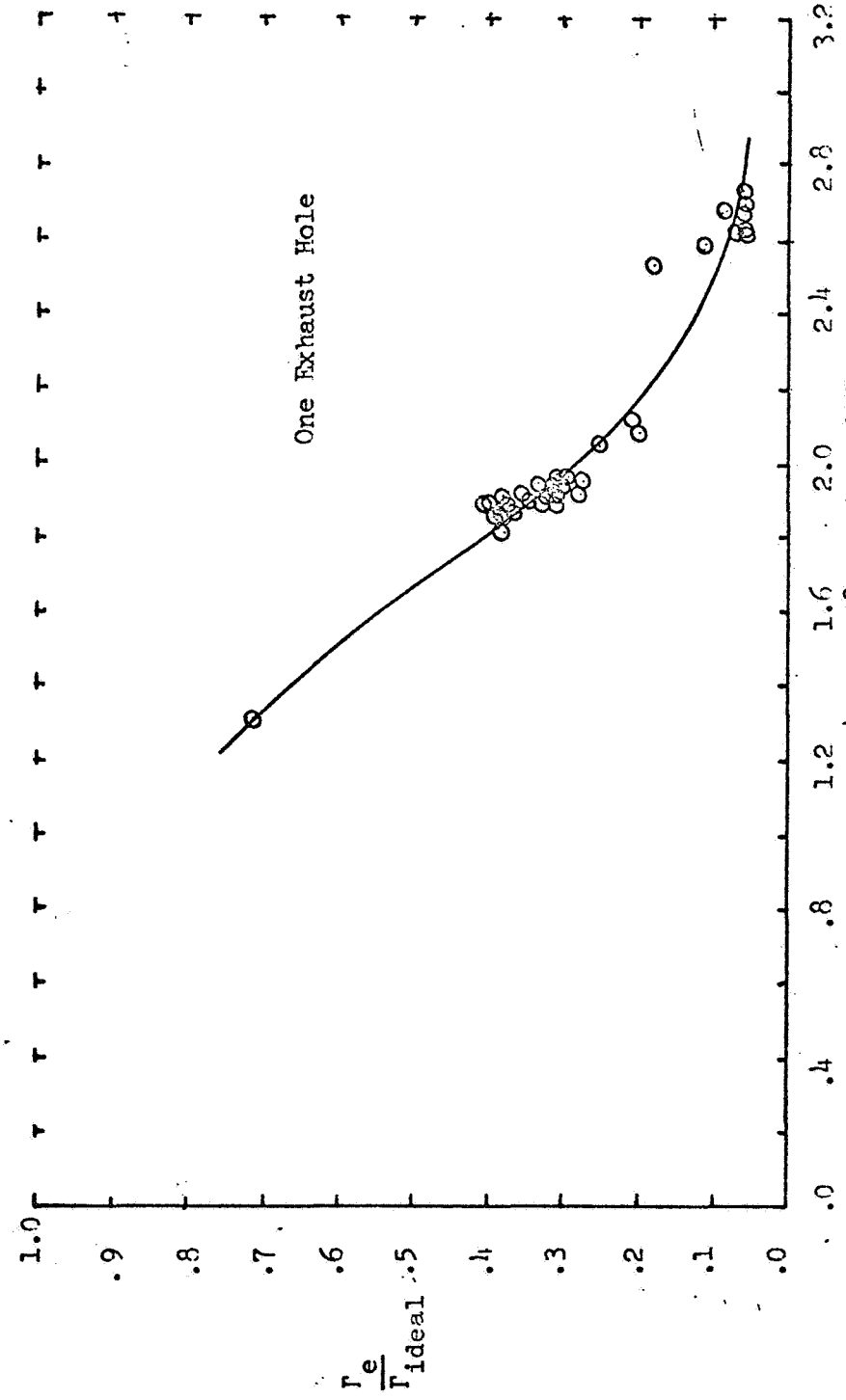

FIG. 8 The ideal circulation ratio as a function of the radius ratio, the wall area ratio, and the pressure ratio.

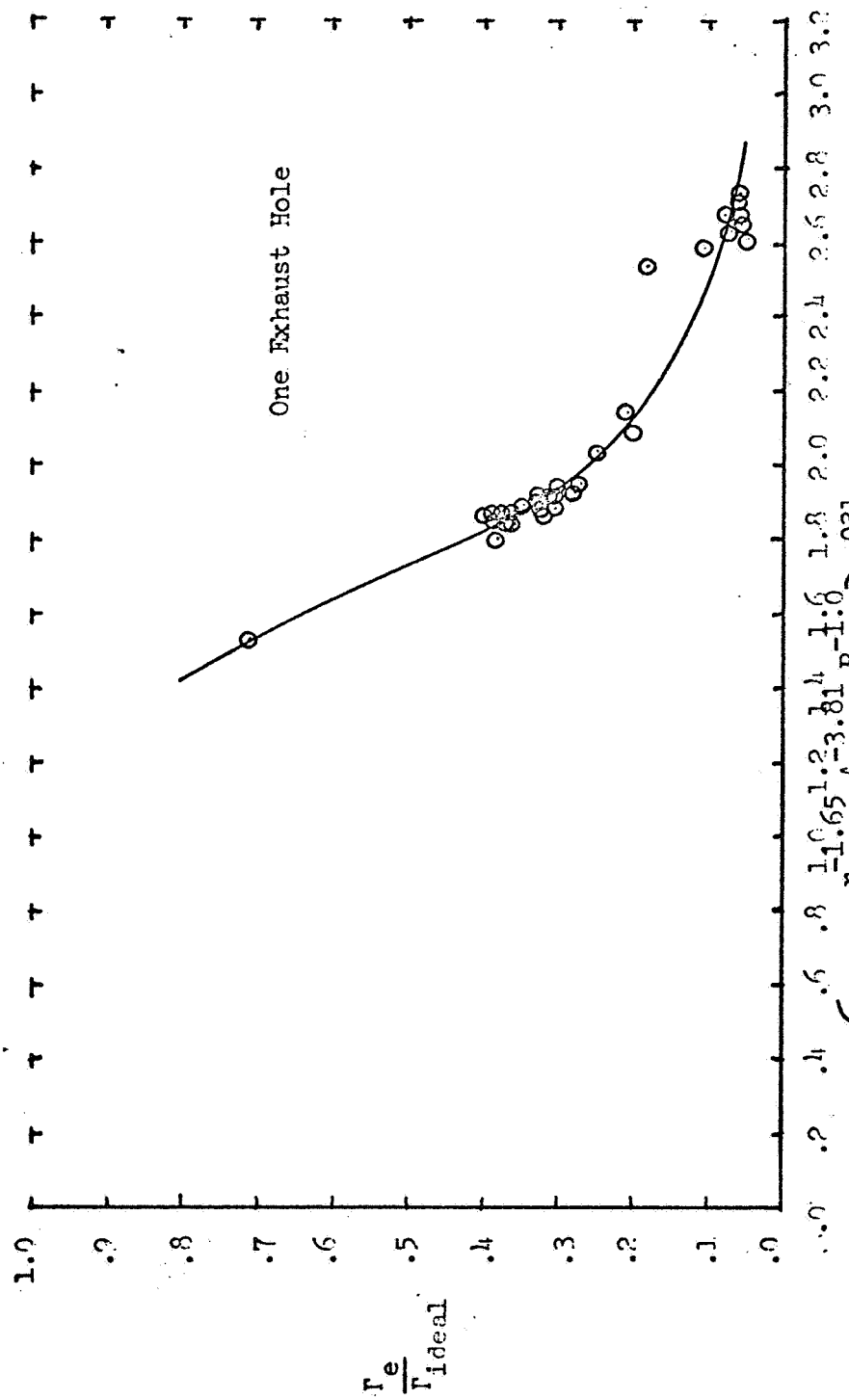

FIG. 9 The ideal circulation ratio as a function of the radius ratio, the total area ratio, and the pressure ratio.

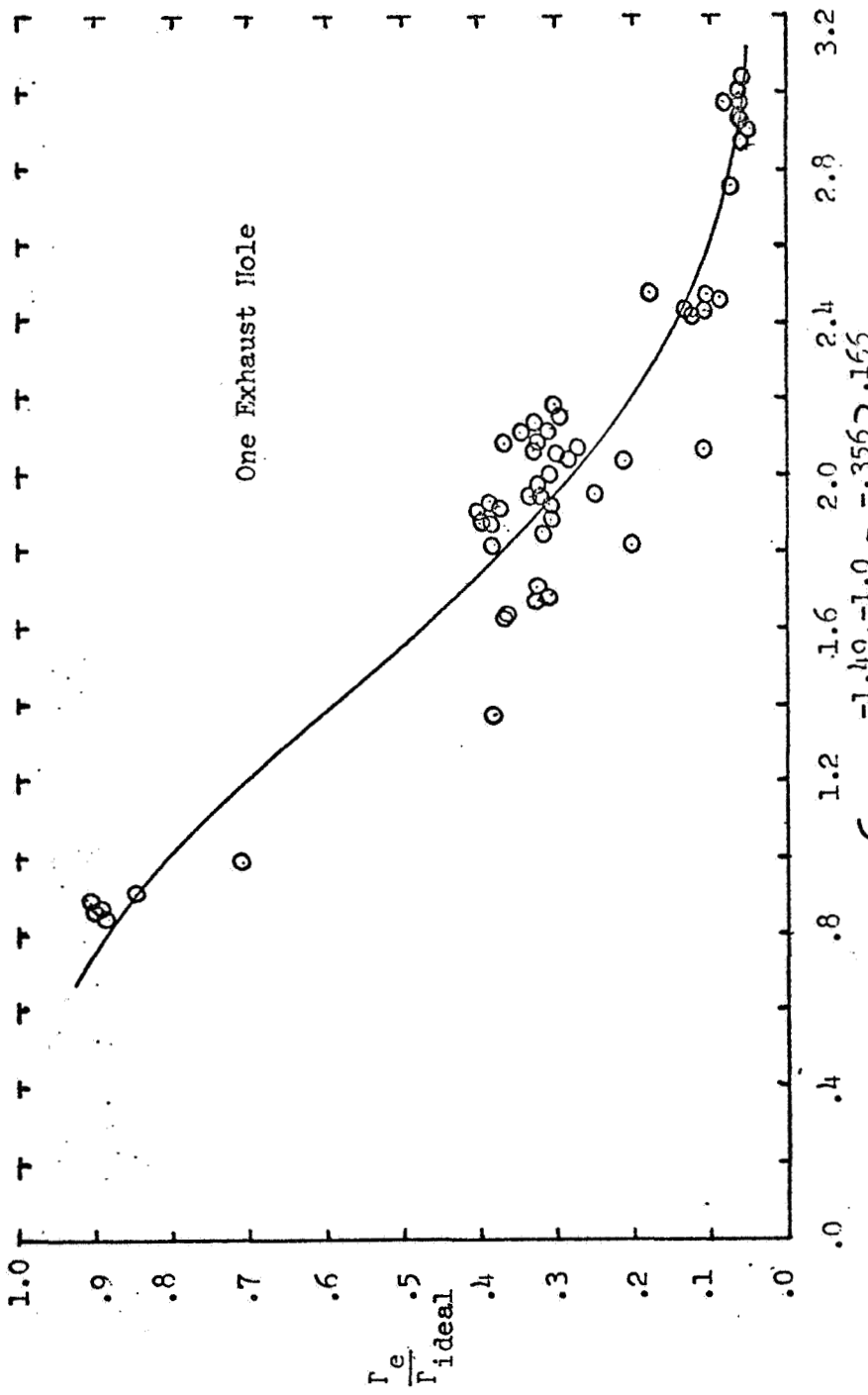

FIG. 10 The ideal circulation ratio as a function of the radius ratio, the wall area ratio, and the tangential Reynolds number.

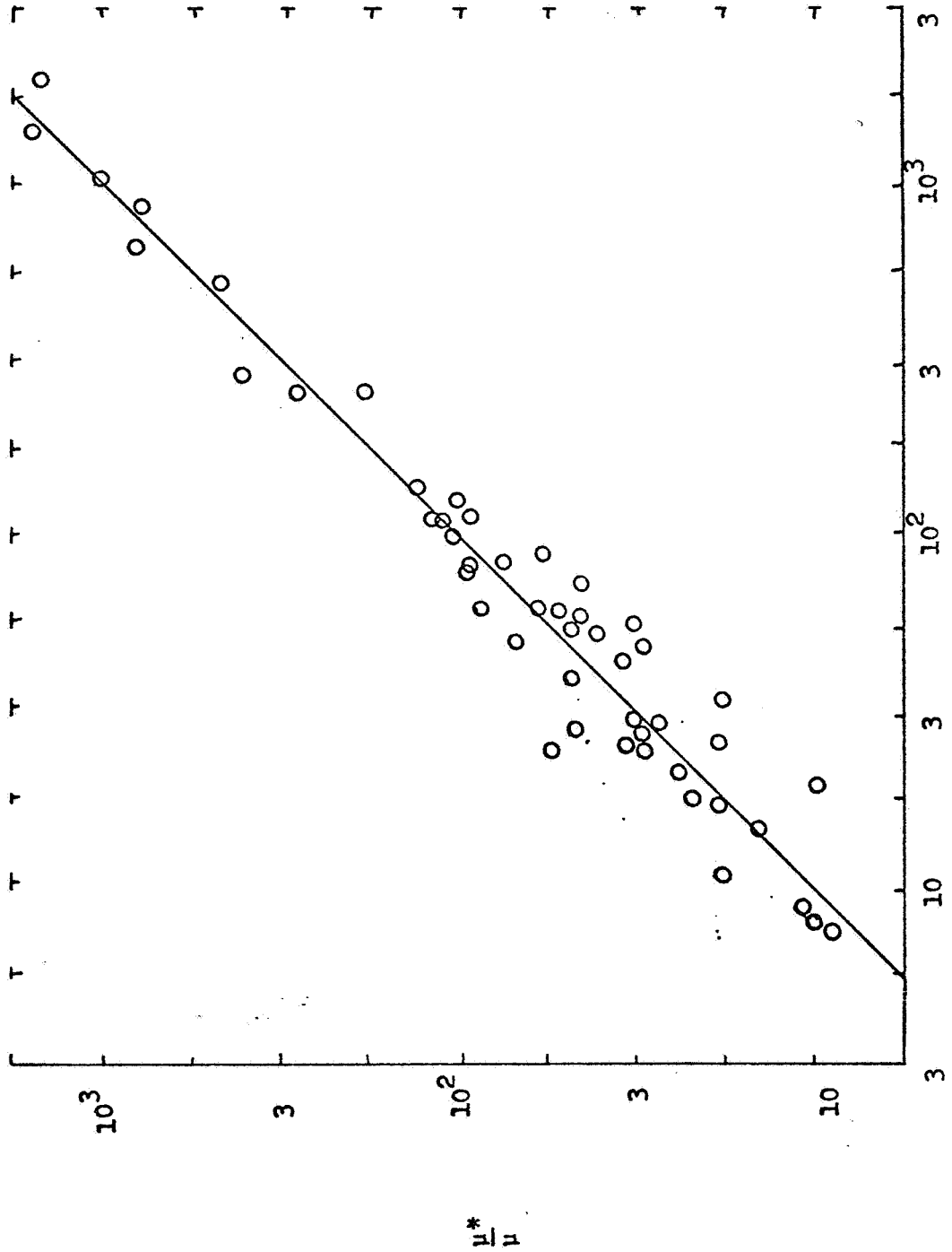

FIG. 12 The ratio of the turbulent "eddy" viscosity as a function of L/D, Re_r, Re_t.

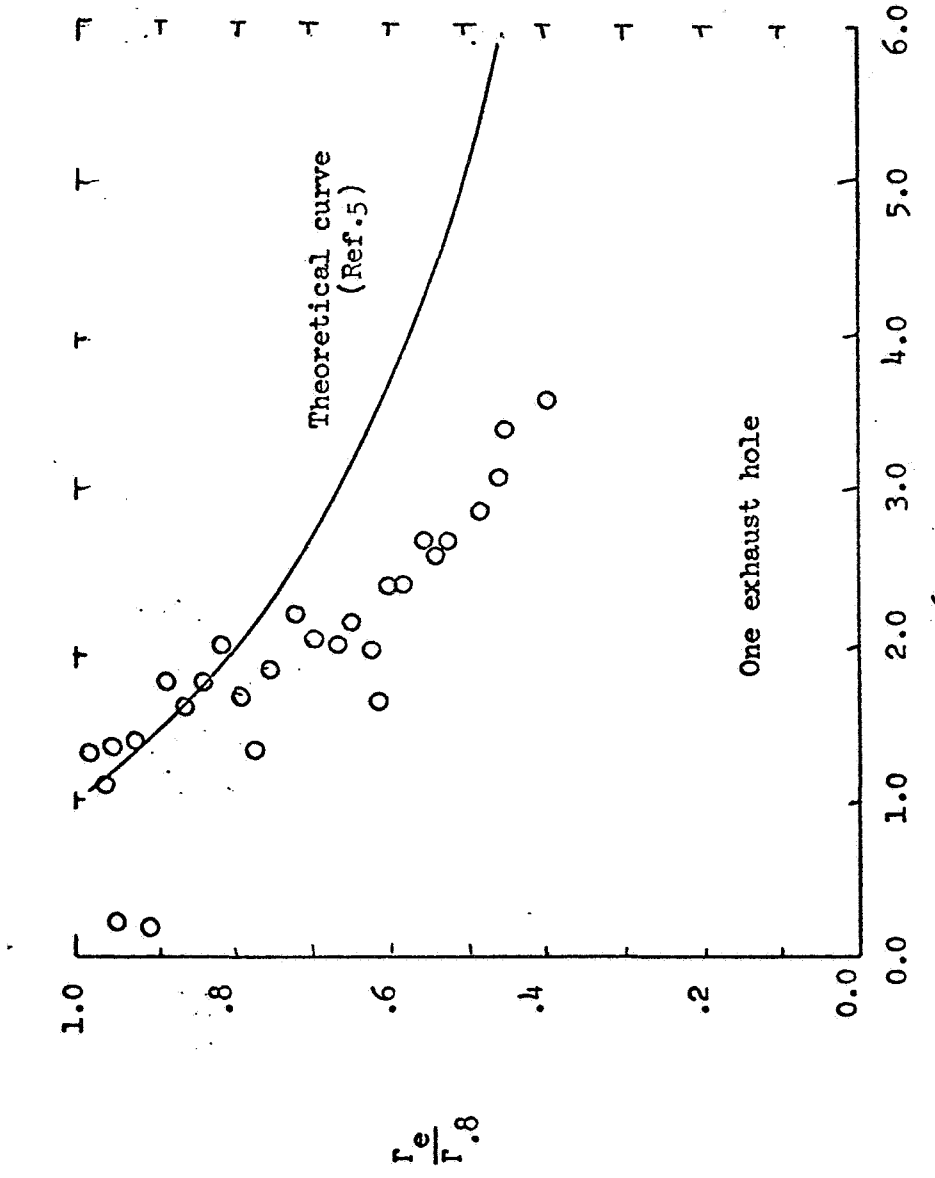

FIG. 11 The circulation ratio as a function of L/D, r_e/r_o, and the boundary layer interaction parameter for incompressible flows.

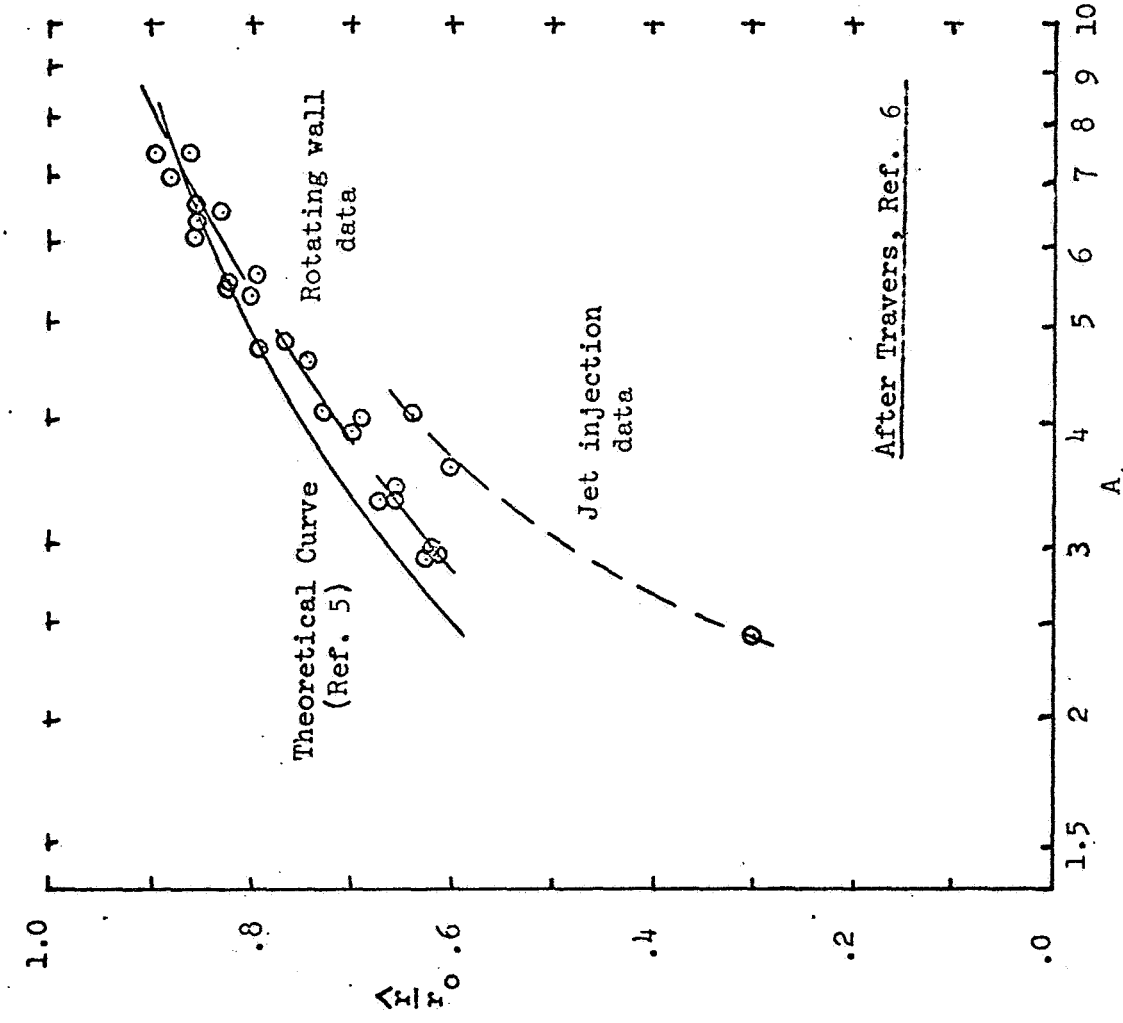

FIG. 13 The normalized radius of stagnation as a function of the boundary-layer interaction parameter (A).